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Brightest Cluster Galaxies and the Las Campanas Distant Cluster Survey

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Abstract. We present our study of the evolution of brightest cluster galaxies based on data from the Las Campanas Distant Cluster Survey (Gonzalez*et al.* 2001) and HST optical and IR imaging. We briefly discuss the technique that enabled us to use short (~ 3 min) exposures and a small (1m) telescope to efficiently survey ~ 130 sq. deg. of sky for high-z galaxy clusters. Follow-up imaging is used to construct a sample of several tens of BCGs at $0.3 \leq z \leq 0.9$ with which to explore their evolution. In particular, we examine the luminosity and color evolution of these galaxies. We confirm the previous results that 1) BCGs in different environments evolve differently (eg. Burke, Collins, & Mann 2000), 2) BCGs, particularly those in low-mass clusters, must be accreting significantly since $z \sim 1$ (Aragon-Salamanca *et al.* 1998). From measurments of the colors vs. redshift, we conclude that this accretion must consist of old stellar populations. Using HST NICMOS and WFPC2 images, we find preliminary evidence for evolution in the sizes of BCGs that is consistent with the accretion model presented in standard hierarchical models (Aragon-Salamanca *et al.* 1998), but puzzling differences between NICMOS and WFPC2 scale lengths precludes a definitive conclusion.

1. Introduction

While definition dictates that every galaxy cluster must have a brightest galaxy, these galaxies are not simply the bright tail of the luminosity function (Oemler 1976; Tremaine & Richstone 1977)). Locally, these galaxies are excellent standard candles (Hoessel 1980) and they appear to remain so to $z \sim 1$ (Aragon-Salamanca et al. 1993; Collins, Burke, and Mann 2000). They appear to be intricately tied to their host cluster because at least some have semimajor axes that extend well beyond 500 kpc (cf. Gonzalez et al. 2000). The evolution of these galaxies is therefore part galaxy evolution, part cluster evolution. The Las Campanas Distant Cluster Survey (LCDCS) provides a new, large sample of clusters with which to construct significant samples of BCGs at $z > 0.5$.

2. The Survey

The basic premise of our cluster detection technique is that we utilize the light from unresolved cluster galaxies. Therefore, we do not need to obtain deep images of the sky to detect a statistically significant number of cluster galaxies, rather we need an image that contains a statistically significant number of cluster photons. The method is described by Dalcanton (1996), Zaritsky *et al.* (1997), and Gonzalez *et al.* (2001).

Our current survey is based on drift scan observations obtained with the Las Campanas 1m Swope telescope and the Great Circle Camera (Zaritsky, Bredthauer, & Shectman 1996). We obtained two scans through each region of the survey area, each with an effective exposure time of ~ 90 s. The power of the technique is evident in the detection of clusters out to $z \sim 1.1$ with a 1m telescope and 3 min exposures. Briefly, the technique involves several flat-fielding passes, masking of bright stars, removal of resolved galaxies and faint stars, and smoothing with a kernel that corresponds roughly to the size of cluster cores at $z \sim 0.6$. We refer the interested reader to Gonzalez *et al.* (2001) for a description of the data reduction techniques and a complete listing of all the candidate clusters.

3. Follow-Up Observations

The most telescope-intensive part of the project has been the follow-up observations aimed at testing our cluster candidates and calibrating methods to estimate the cluster redshift and mass (see below). From imaging in V, I, and K', we construct a sample of BCGs drawn from photometry of 63 confirmed galaxy clusters (not all are imaged in each filter).

With surveys that produce thousands of candidate galaxy cluster identifications, it becomes impractical to obtain redshift and mass measures via spectroscopy for a significant fraction of the candidates. Ideally, these quantities can be estimated from the survey data themselves. In doing so, we will necessarily sacrifice precision on a cluster-by-cluster basis, but as long as the uncertainties are well understood, the sheer number of clusters allows high precision measures of the statistical properties of the sample. There really is no choice in this matter - to obtain a sufficient number of galaxy spectroscopic redshifts for mass

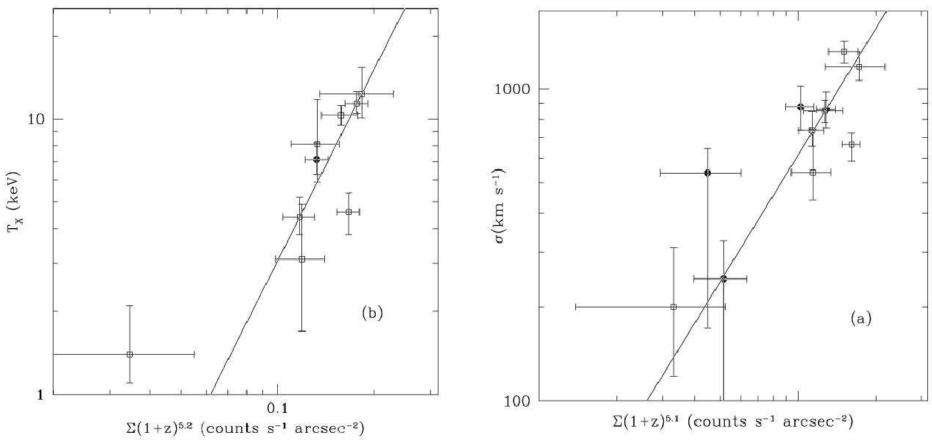

Figure 1. X-ray temperature and galaxy velocity dispersion vs. optical central surface brightness, Σ

measurements of a sample of ONLY 20 clusters requires $\sim$ 35 nights on an 8 to 10m class telescope.

We use cluster spectroscopic redshifts when available, or photometric redshifts based on the color of the red sequence of early-type galaxies in the cluster (Nelson *et al.* 2001a). The calibration of the mass indicator is much more speculative primarily because of the dearth of mass estimates for high redshift clusters. Only one previously known X-ray cluster at $z > 0.35$ lies within our survey area. To augment this, we did small drift scans around 17 other clusters with X-ray luminosity and/or temperature measurements. Unfortunately, the relationships between Σ and other mass indicators (L_x, T_x, or velocity dispersion) are somewhat poorly defined (Figure 1). Two aspects are particularly vexing: 1) we need to determine not only the relation between these quantities but we also need to quantify the scatter to successfully apply this method, and 2) most of the data are for clusters at the low end of the redshift range. Extracting the full potential of this, or any other survey, is predicated on developing a reliable mass estimator and understanding its uncertainties. Nevertheless, these correlations enable us to split the sample into likely low-L_X and high-L_X subsamples to investigate the role of environment on BCG properties.

Selecting the BCG is often non-trivial because of contamination and the definition of a selection radius. Due to space limitations we do not discuss this issue further here (a full discussion is presented by Nelson *et al.* 2001a).

4. Luminosity and Color Evolution and the Nature of the Accretion

We show the I-band BCG Hubble diagram in Fig 2. In the lower panel we bin the data along redshift to reveal the mean trends. At $z < 0.6$ the average BCG appears to follow the no-evolution prediction, while at high redshifts they appear to begin to edge toward the passive evolution model. We find that this peculiar behavior is due to the inclusion of BCGs from a wide range of

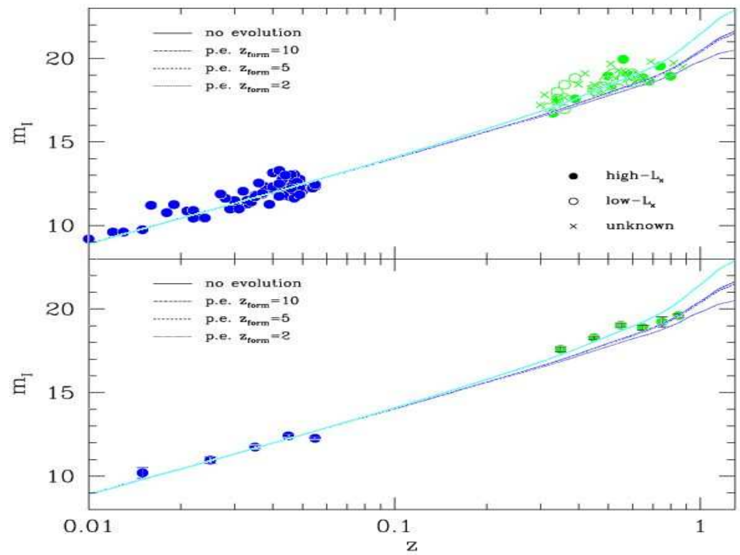

Figure 2. *I*-band BCG Hubble Diagram. Symbols in the upper panel represent individual BCGs, symbols in the lower panel represent the means in redshift bins. The BCGs at $z < 0.1$ are from Graham *et al.* Clusters with 'unknown' values of L_X at $z > 0.6$ are almost certainly high-L_X clusters because those are the only ones sufficiently bright to be detected. The model lines are described in the upper left of each panel (p.e. = passive evolution).

clusters. In particular, as we discuss next, we find that the BCGs in clusters with $L_X > 2 \times 10^{44}$ ergs s^{-1} lie along the passive evolution models, while the BCGs in fainter clusters lie along the no-evolution models. The different relative fraction of the two types of BCGs at different redshifts leads to the initially perplexing Hubble diagram.

Following the suggestion by Burke, Collins, & Mann (BCM) that 2×10^{44} ergs s^{-1} may be an appropriate division of cluster types at these redshifts, we have divided our sample at the corresponding value of the central surface brightness. Because at $z > 0.6$ our clusters fall primarily in the high L_X sample, the high L_X sample is consistent with passive evolution models. The low L_X sample, which is primarily our lower redshift sample, is consistent with no-evolution models.

Aragon-Salamanca, Baugh and Kauffmann (1998) interpreted consistency with no-evolution models to indicate the presence of accretion (because no-evolution is non-physical). They inferred that these galaxies accreted 2 to 4 times their mass since a redshift of one. BCM found that these results were derived primarily from a sample of BCGs in low-L_X clusters and concluded that much lower (by a factor of 2) rates were upper limits on the accretion for BCGs in the more massive environments. Qualitatively, we confirm both results (accretion is necessary in BCGs in low-L_X environments and less (or no) accretion is necessary in BCGs in high-L_X environments).

Our data in V, I, and K' allow us to investigate the color evolution of BCGs. In contrast to the situation for luminosity evolution, the color evolution

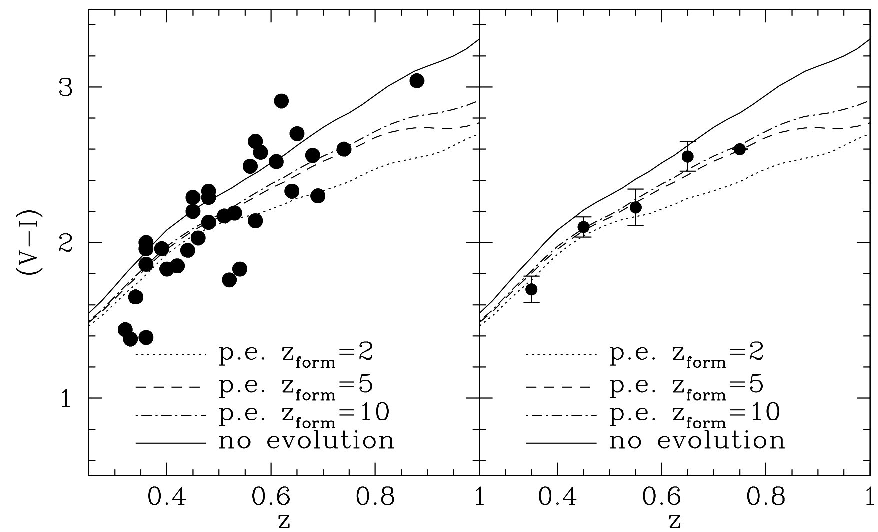

Figure 3. $V - I$ Color Evolution of BCGs. Left panel contains all of our BCGs for which V and I data are available and the right panel contains the same data binned by redshift. The sole galaxies beyond $z \sim 0.85$ is not included in the binned version.

is consistent with passive evolution for both the low and high L_X samples (Figure 3). In all cases the stellar populations of these galaxies appear to be rather old, passively evolving. Therefore, whatever accretion is occurring, it consists of old stellar populations, not the accretion of gas (i.e. a cooling flow) or of gas-rich galaxies, which would presumably lead to a starburst. Interestingly, this result fits in well with the recent discovery of red mergers at high redshift (van Dokkum *et al.* 2000 in MS1054-03).

5. The Search for Direct Evidence of Accretion

If significant accretion is occurring, can we see the structural properties of BCGs change with redshift? If BCGs have velocity dispersions that are nearly independent of mass (as seen locally Malumuth & Kirshner 1981, 1985; Oegerle & Hoessel 1991), then changes in their masses must be reflected by changes in their sizes. If BCG surface brightness profiles can be characterized by deVaucouleurs profiles (see Graham *et al.* 1996; Gonzalez *et al.* 2000 for a variety), then a measure of their effective radii will provide a measure of their size. The nature of the profiles at large radius is still a subject of debate (cf. Schombert 1986; Graham *et al.* 1996; Gonzalez *et al.* 2000), so it is possible that BCGs could change size and yet retain a constant scale length at smaller radii (therefore, a null result with regard to scale length changes as a function of redshift may not rule out accretion).

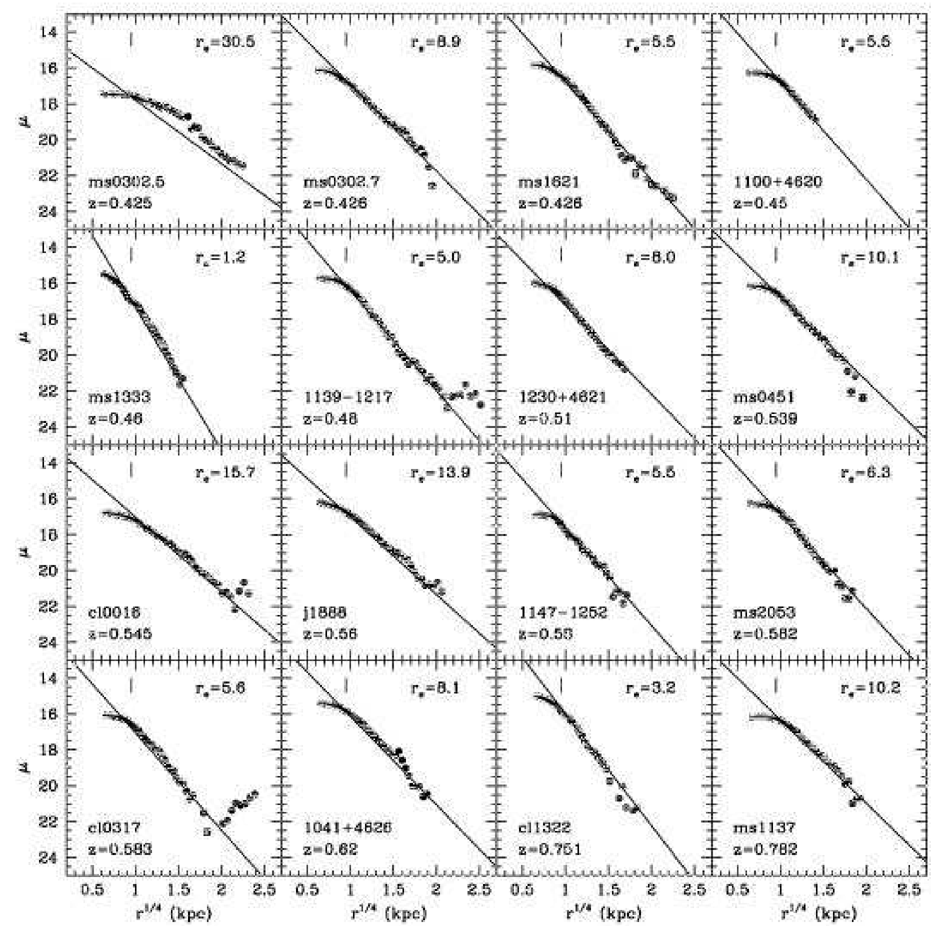

Figure 4. H-band NICMOS Surface Brightness Profiles of High-z BCGs. The vertical tick mark in each panel represents the resolution limit.

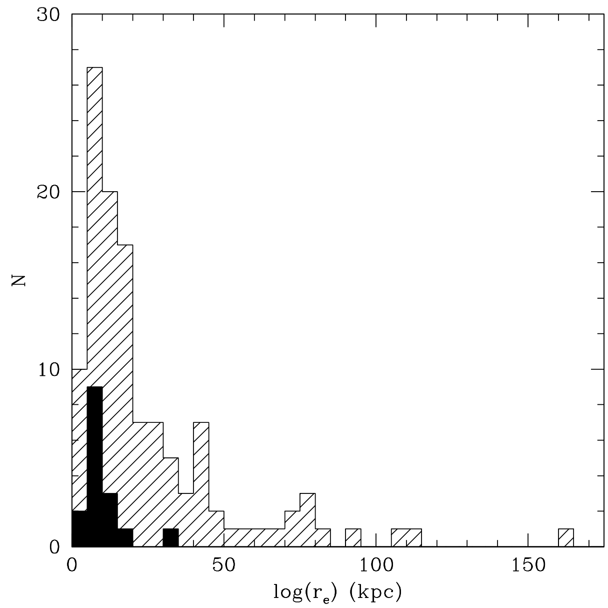

Figure 5. Comparison of Scale Lengths of Local and Distant BCGs. Hashed histogram is the distribution of effective radii for local BCGs and the filled histogram is the result from our NICMOS snapshots (Nelson *et al.* 2001).

Using NICMOS snapshots of 16 BCGs in a heterogeneous sample of literature clusters at a mean redshift of ~ 0.5, to which we have fitted de Vaucouleurs profiles using the Gim2D software (Simard 1998), we measure the distribution of scale lengths and compare to that measured from a local sample by Graham *et al.* For all but one of the galaxies the $r^{1/4}$-law profiles fit well (Figure 4). Comparison to similar measurements on archival WFPC2 images of the BCGs for which some images are available, suggests that non-uniform sky variations in the IR may lead us to underestimate the scale length by as much as 30% systematically. Although the high-redshift sample has a mean scale length that is smaller than that of the local sample by somewhere between 20 and 50% (Figure 5), this result is preliminary because of the nagging systematic problems in resolving differences in scale lengths obtained from NICMOS and WFPC2 data (possibly due in part to physical effects like color gradients). Neither the WFPC2 nor NICMOS images match the rest wavelength of the local sample, and the differences we find between WFPC2 and NICMOS suggest that scale length depends sensitively on color. The magnitude of the accretion necessary to account for the luminosity evolution is within reach of size measurements of BCGs, once the color-dependence of the scale-lengths is understood.

6. Conclusions

Using a completely independent sample of high-redshift BCGs we have confirmed the results of previous investigators: 1) BCG properties vary as a function of environment, 2) BCGs in low-L_X clusters require significant accretion (a factor

of 2 or more since $z \sim 1$) to produce the observed Hubble diagram, and 3) BCGs in high-L_X clusters require much less (or possibly no) accretion to produce the observed Hubble diagram. Additionally, we find that the accretion must consist of old stellar populations (because the colors of both BCG populations are consistent with passive evolution models) and that the sizes of high-redshift BCGs appear to be smaller than that of the local counterparts by a factor that is consistent with the accretion model. Further study of BCGs may provide the first truly direct observations of the hierarchical growth of a galaxy population.

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